J. Cent. South Univ. (2013) 20: 1938−1946
DOI: 10.1007/s11771-013-1693-6

Springer

Effects of working parameters on gasoline engine exergy balance

LIU Jing-ping(刘敬平)[1], FU Jian-qin(付建勤)[2], FENG Ren-hua(冯仁华)[1], ZHU Guo-hui(朱国辉)[2]

1. Research Center for Advanced Powertrain Technology, Hunan University, Changsha 410082, China;
2. State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body (Hunan University), Changsha 410082, China

Abstract: To improve the energy utilization efficiency of internal combustion (IC) engine, exergy analysis was conducted on a passenger car gasoline engine. According to the thermodynamic theory of IC engine, in-cylinder exergy balance model was built. The working processes of gasoline engine were simulated by using the GT-power. In this way, the required parameters were calculated and then gasoline engine exergy balance was obtained by programming on computer. On this basis, the influences of various parameters on exergy balance were analyzed. Results show that, the proportions of various forms of exergy in gasoline engine from high to low are irreversible loss, effective work, exhaust gas exergy and heat transfer exergy. Effective exergy proportion fluctuates with cylinder volumetric efficiency at full load, while it always increases with break mean effective pressure (BMEP) at part load. Exhaust gas exergy proportion is more sensitive to speed, and it increases with speed increasing except at the highest speed. The lower proportion of heat transfer exergy appears at high speed and high load. Irreversible loss is mainly influenced by load. At part load, higher BMEP results in lower proportion of irreversible loss; at full load, the proportion of irreversible loss changes little except at the highest speed.

Key words: gasoline engine; exergy balance; waste heat recovery; thermal efficiency; energy conservation

1 Introduction

Because of many advantages such as wide range of power and speed, and high thermal efficiency, internal combustion engine (IC engine) has been widely used in most kinds of fields. The power produced by IC engine accounts for more than half of the total power in the world. Thus, IC engine plays an irreplaceable role in the society especially in the transportation. However, it consumes more than 60% of fossil oil and at the same time it is one of the most pollution sources which produce lots of harmful gases, such as CO and HC. For the sake of pursuing higher fuel utilization efficiency of IC engine and reducing the emission of greenhouse gas CO_2, scientists and scholars have done lots of research in this direction. As a kind of thermal engine, the working principle of IC engine follows the basic theory of thermodynamics. Usually, the working processes of IC engine were abstracted to an ideal thermodynamic cycle, which consists of various kinds of thermodynamic processes [1]. On this basis, energy balance method was used for studying and optimizing the process of energy transformation and transmission in IC engine [2−3]. However, the traditional method of energy balance based on the first law of thermodynamics only considers the quantity of various forms of energy in IC engine. It can not reflect the irreversible loss in the work processes, because no matter how perfect the IC engine system is, various kinds of energy in the system always keep balance. On the contrary, under any circumstance, exergy balance can figure out the irreversible loss caused by irreversible process, and reveal the quality change of energy in real process [4].

During the working process of IC engine, fuel chemical energy converts into thermodynamic energy of gas medium through combustion. Then, part of thermodynamic energy is used to push the piston, while the rest is lost due to cylinder wall heat transfer, exhaust gas loss and other irreversible loss. Obviously, all the processes occurring in IC engine are irreversible process. According to the second law of thermodynamics, irreversible process inevitably leads to exergy loss. Consequently, both the quantity and quality relationship among various forms of energy should be taken into account in IC engine. As a result, exergy analysis based on the second law of thermodynamics is another useful way to evaluate the energy utilization efficiency of IC engine, and it has become a new hotspot which is concerned by scientists and scholars recently [4−9]. For

Foundation item: Project(2011CB707201) supported by the National Basic Research Program of China; Project(10JJ5058) supported by the Natural Science Foundation of Hunan Province, China
Received date: 2012−04−20; **Accepted date:** 2013−02−03
Corresponding author: FU Jian-qin, PhD; Tel: +1−3134215709; E-mail: fujianqinabc@163.com

example, RAKOPOULOS and GIAKOUMIS [5] carried out the research on exergy analysis of transient diesel engine operation; WANG [6] studied the diesel engine working process by using the method of exergy analysis. However, little attention has been devoted to the exergy analysis on gasoline engine so far, and the data about gasoline engine exergy distribution are still scarce. Therefore, further studies are still necessary. The purpose of this work is to extend the research on gasoline engine exergy balance by using the method of numerical calculation. Through drawing the relationship between the working parameters of gasoline engine and various kinds of exergy distributions, the approach to improve gasoline engine exergy efficiency is acquired eventually.

2 Basic theory of exergy analysis on gasoline engine

2.1 Exergy balance model based on cylinder

The energy conversion process of IC engine is generalized as follows. Firstly, fuel chemical energy converts into gas medium thermal energy by combustion, and then part of thermal energy transforms into the effective work of piston while the remainder is lost in waste heat. According to the second law of thermodynamics, fuel chemical energy is a kind of high-grade energy whose quality factor is approximated to be 1 [10]. Meanwhile, thermal energy is a kind of medium-grade energy whose quality factor depends on the temperature and is less than 1. However, waste heat energy is a kind of low-grade energy, and its quality factor is far less than 1. As a result, the energy grade in IC engine descends during the energy conversion process. In other words, there are various kinds of exergy losses due to various kinds of irreversible factors. According to the exergy theory, higher exergy efficiency of IC engine means better fuel economy and energy utilization efficiency. During the process of energy conversion in IC engine, exergy loss is inevitable.

Taking a cylinder as control volume, the exergy balance model is built, as shown in Fig. 1. There are several kinds of exergy flow into and out of the cylinder. The exergy that flows into cylinder includes intake gas exergy and fuel chemical exergy, while the exergy that flows out of cylinder consists of effective work, heat transfer exergy, exhaust gas exergy and irreversible loss. Besides, there is a balance between the exergy flows into cylinder and the exergy flows out of cylinder. The exergy flows out of cylinder can be defined as exergy loss except effective work. Also, exergy loss can be classified into external exergy loss and internal exergy loss. External exergy loss consists of exhaust gas exergy and heat transfer exergy, both of which are generated by energy transfer. However, internal exergy loss is derived from the irreversible factors of real process, and it is also called irreversible loss, which mainly includes burning loss, friction loss and throttling loss.

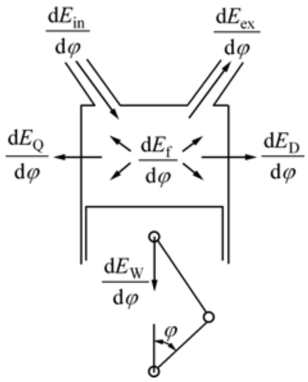


Fig. 1 Schematic diagram of exergy balance in cylinder

2.2 Exergy balance equations

Combined with the schematic diagram of exergy balance model shown in Fig. 1, the differential equation of exergy balance based on IC engine cylinder system is given by [11]

$$\frac{dE_{in}}{d\varphi}+\frac{dE_f}{d\varphi}=\frac{dE_W}{d\varphi}+\frac{dE_Q}{d\varphi}+\frac{dE_{ex}}{d\varphi}+\frac{dE_s}{d\varphi}+\frac{dE_D}{d\varphi} \tag{1}$$

where $dE_{in}/d\varphi$ is the intake gas exergy; $dE_f/d\varphi$ is the fuel chemical exergy; $dE_W/d\varphi$ is the effective work; $dE_Q/d\varphi$ is the heat transfer exergy in cylinder; $dE_{ex}/d\varphi$ is the exhaust gas exergy; $dE_s/d\varphi$ is the change of working medium exergy in cylinder; $dE_D/d\varphi$ is the irreversible exergy loss generated in actual process; φ is the IC engine crankshaft angle.

In a complete working cycle, the working medium exergy has no change. Moreover, for the sake of analyzing the distribution of fuel exergy, Eq. (1) can be written as

$$E_f=E_W+E_Q+(E_{ex}-E_{in})+E_D \tag{2}$$

In Eq. (2), E_{ex} minus E_{in} equals the net exergy taken away by exhaust gas.

Next, the calculation formulas for each item in Eq. (1) are given.

1) Intake gas exergy:

$$\frac{dE_{in}}{d\varphi}=[h_1-h_0-T_0(s_1-s_0)]\frac{dm_{in}}{d\varphi} \tag{3}$$

where h_1 is the specific enthalpy of intake gas, which can be calculated by interpolation according to intake gas temperature; h_0 is the specific enthalpy of ambient air; T_0 is the environment temperature; s_1 is the specific entropy of intake gas, which can also be calculated by interpolation according to intake gas temperature; s_0 is the specific entropy of ambient air; $dm_{in}/d\varphi$ describes the

relationship between instantaneous mass flow rate of intake gas and IC engine crankshaft angle.

2) Fuel chemical exergy [10]:

$$\frac{\mathrm{d}E_\mathrm{f}}{\mathrm{d}\varphi}=H_\mathrm{L}(1.003\,8+0.136\,5\frac{w(\mathrm{H})}{w(\mathrm{C})}+0.030\,8\frac{w(\mathrm{O})}{w(\mathrm{C})}+0.010\,4\frac{w(\mathrm{S})}{w(\mathrm{C})})\frac{\mathrm{d}m_\mathrm{f}}{\mathrm{d}\varphi} \tag{4}$$

where H_L is the low heat value of fuel; $w(\mathrm{H})$, $w(\mathrm{C})$, $w(\mathrm{O})$ and $w(\mathrm{S})$ represent the mass fractions of hydrogen, carbon, oxygen and sulfur in fuel, respectively; m_f is the mass flow rate of fuel.

3) Piston effective work:

$$E_\mathrm{W}=\frac{3\,600P_\mathrm{e}\tau}{60n\cdot i} \tag{5}$$

where P_e is the effective power of IC engine; τ is a constant depending on the number of stroke, and it is taken as 2 in four-stroke IC engine while 1 in two-stroke IC engine; n is the IC engine speed; i is the cylinder number.

4) Heat transfer exergy in cylinder:

$$\frac{\mathrm{d}E_\mathrm{Q}}{\mathrm{d}\varphi}=\frac{\mathrm{d}Q_\mathrm{W}}{\mathrm{d}\varphi}(1-\frac{T_0}{T}) \tag{6}$$

where Q_W is the heat transfer quantity from cylinder wall; T is the working medium temperature in cylinder.

5) Exhaust gas exergy:

$$\frac{\mathrm{d}E_\mathrm{ex}}{\mathrm{d}\varphi}=[h_\mathrm{ex}-h_0-T_0(s_\mathrm{ex}-s_0)]\frac{\mathrm{d}m_\mathrm{ex}}{\mathrm{d}\varphi} \tag{7}$$

where h_ex and s_ex are the specific enthalpy and specific entropy of exhaust gas, respectively, both of which can be calculated by interpolation according to exhaust gas temperature and composition; $\mathrm{d}m_\mathrm{ex}/\mathrm{d}\varphi$ describes the relationship between instantaneous mass flow rate of exhaust gas and IC engine crankshaft angle.

6) Internal exergy loss:

$$E_\mathrm{D}=E_\mathrm{f}-E_\mathrm{W}-E_\mathrm{Q}-(E_\mathrm{ex}-E_\mathrm{in}) \tag{8}$$

For the purpose of analyzing the distribution of fuel chemical exergy, the percentage of each kind of exergy in total fuel exergy is proposed. As a result, Eq. (2) can be rewritten as

$$\eta_\mathrm{e}+\eta_\mathrm{Q}+\eta_\mathrm{g}+\eta_\mathrm{D}=100\% \tag{9}$$

where η_e is the percentage of effective exergy, and it can also be defined as exergy efficiency,

$$\eta_\mathrm{e}=\frac{E_\mathrm{W}}{E_\mathrm{f}}\times 100\% \tag{10}$$

η_Q is the percentage of heat transfer exergy,

$$\eta_\mathrm{Q}=\frac{E_\mathrm{Q}}{E_\mathrm{f}}\times 100\% \tag{11}$$

η_g is the percentage of exhaust gas exergy,

$$\eta_\mathrm{g}=\frac{E_\mathrm{ex}-E_\mathrm{in}}{E_\mathrm{f}}\times 100\% \tag{12}$$

η_D is the percentage of internal exergy loss,

$$\eta_\mathrm{D}=\frac{E_\mathrm{D}}{E_\mathrm{f}}\times 100\% \tag{13}$$

In this work, calculation base point is set to the standard atmospheric state, that is, P_0=0.1 MPa and T_0=298.15 K.

3 Numerical calculation on working process of gasoline engine

3.1 Numerical model of gasoline engine

The study object in this work is a naturally aspirated gasoline engine for passenger car, whose basic parameters are listed in Table 1. According to the structure and performance parameters of this gasoline engine, the performance simulation model is built by using the GT-power simulation software. GT-power is a kind of one-dimensional performance simulation software for IC engine. It can not only simulate the working process of IC engine, but also exactly calculate the flow and heat transfer processes of thermal fluid through dispersing the entire range of 0°−720° crankshaft angle. On this basis, both the energy exchange process and mass exchange process in cylinder can be accurately calculated at each IC engine crankshaft angle. A lot of experimental data show that GT-power software has a high precision in calculating IC engine performance and thermal fluid. The simulation model of target gasoline engine consists of three parts, which are intake system, cylinder and crankcase, exhaust system, as shown in Fig. 2.

In this model, the boundary conditions of inlet and

Table 1 Basic parameters of gasoline engine

Item	Content
Gasoline engine type	Inline 4 cylinder, 4 stroke
Bore/mm	66
Stroke/mm	74
Displacement/L	1.02
Compression ratio	9.5
Ignition mode	1-3-4-2
Rated power/kW	43.6
Max torque/(N·m)	82.8
Intake mode	Naturally aspirated
Cooling mode	Water-cooled

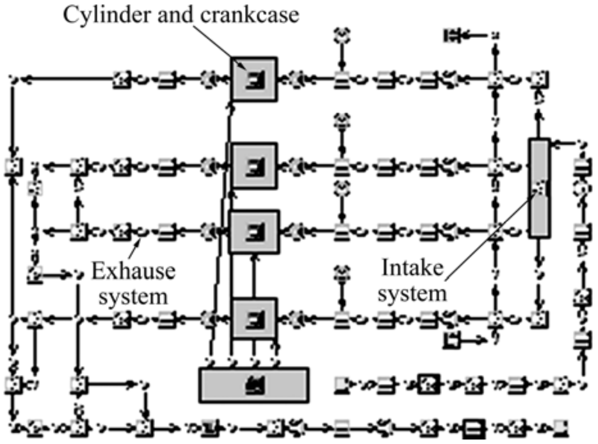


Fig. 2 GT-power simulation model for gasoline engine

outlet, such as temperature and pressure, were set to the standard atmospheric state. Other parameters, including mechanical friction loss, combustion efficiency and air/fuel ratio, etc, were calibrated by gasoline engine experimental data. The flow coefficients of intake valve and exhaust valve were acquired by airway test. The resistance coefficient and heat transfer coefficient of pipe wall were obtained through looking-up the tables of material properties.

3.2 Calibrating gasoline engine model

Since the content of this work is largely based on computer simulation results, a figure comparing the measured and calculated data of the gasoline engine is necessary to show that the computer simulation model is reliable. After the calculation model was built, part of calculation results of this GT-power model, e.g. torque and mass flow rate of intake gas, were compared to the corresponding experimental data for the purpose of verifying the credibility and precision of this model, as shown in Fig. 3. Figure 3(a) shows the comparison results of torque at various kinds of gasoline engine speed, while Fig. 3(b) shows the comparison results of mass flow rate of intake gas. The results show good agreement between the calculation data and experimental data, and this demonstrates that the model has enough precision to simulate the work process of this gasoline engine.

Next, the gasoline engine model was simulated at both full load (speed range is 1 000−6 000 r/min) and part load (load range is 0.2−1.0 MPa), for the purpose of getting various kinds of required parameters. On this basis, exergy balance of this gasoline engine was calculated by using the programming on computer according to those equations given in Eqs. (1)−(13). Finally, the influences of working parameters on gasoline engine exergy balance were analyzed, and the results were given in the next section.

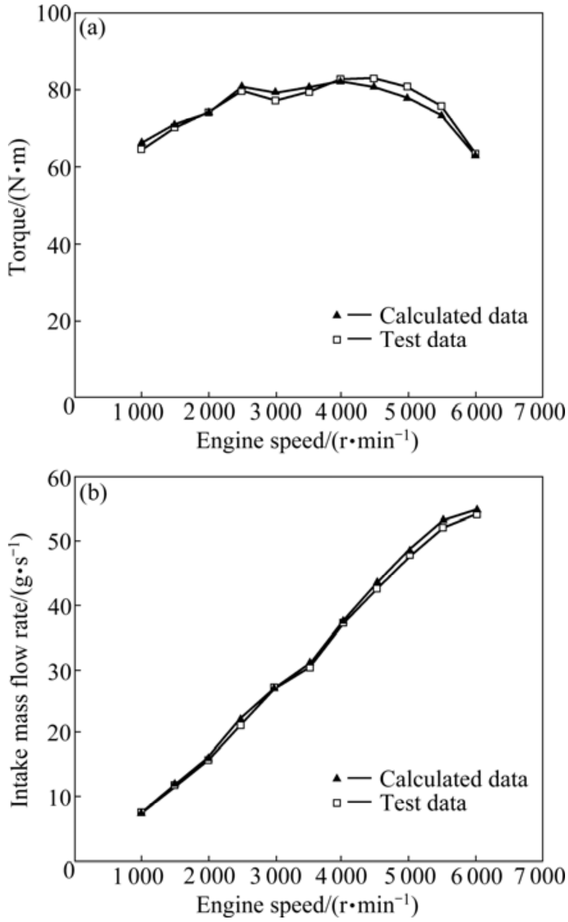


Fig. 3 Comparison of calculation results and measured data (full load): (a) Torque vs gasoline engine speed; (b) Intake mass flow rate vs gasoline engine speed

4 Results and analysis

4.1 Gasoline engine exergy balance at full load

First of all, the effects of speed on gasoline engine exergy balance at full load are analyzed. Figures 4(a)−(d) show various kinds of exergy in each cylinder and each working cycle, including effective work, heat transfer exergy, exhaust gas exergy and irreversible exergy loss. As shown in Fig. 4(a), effective work in each cycle first increases and then decreases with the gasoline engine speed increasing. This phenomenon is mainly determined by the working characteristic of gasoline engine. As the research object is a naturally aspirated gasoline engine, cylinder volumetric efficiency determines the intake gas mass in each working cycle. Furthermore, it influences the effective work since the air-to-fuel ratio of gasoline engine is almost fixed. In accordance with our previous research [12], the variation tendency of volumetric efficiency of multi-cylinder engine first increases and then decreases with the speed increasing. As a result, volumetric efficiency determines the effective work ultimately. Figure 4(b) gives the heat transfer exergy in cylinder during per working cycle. As can be seen,

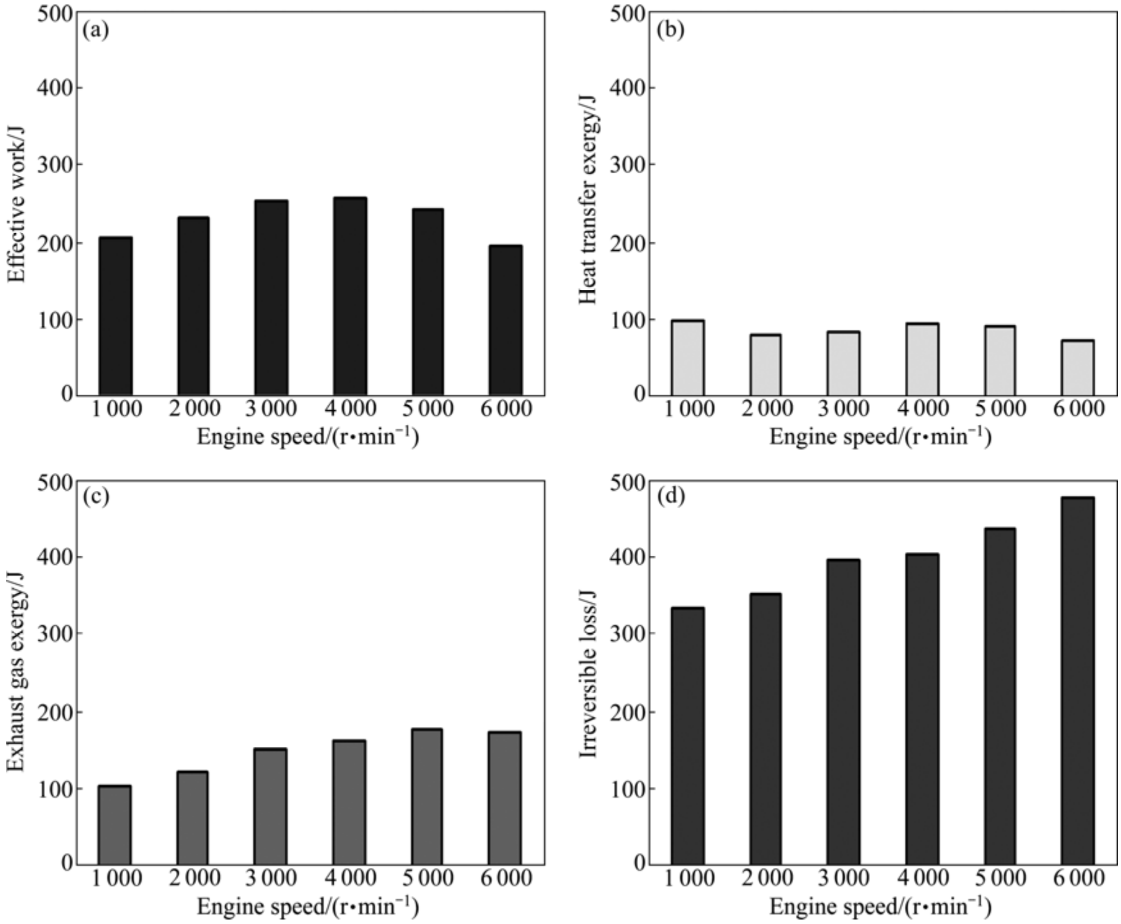


Fig. 4 Various kinds of exergy at full load: (a) Effective work per cycle; (b) Heat transfer exergy per cycle; (c) Exhaust gas exergy per cycle; (d) Irreversible loss per cycle

gasoline engine speed has little effect on heat transfer exergy. This is because heat transfer exergy depends on both the heat transfer quantity and in-cylinder temperature. However, there is a reciprocal relationship between the two kinds of parameters. At low speed, heat transfer quantity is larger since heat transfer time in each cycle is longer, but heat transfer exergy is limited by the lower in-cylinder temperature. With the increase of speed, heat transfer quantity in each cycle decreases sharply as heat transfer time is reduced, but heat transfer exergy receives certain compensation because in-cylinder temperature increases. As shown in Fig. 4(c), exhaust gas exergy increases as gasoline engine speed ascends. This is because exhaust gas temperature increases gradually with speed increasing. At the speed of 5 000 r/min and 6 000 r/min, the increase rate of exhaust gas exergy per cycle is very small or even has no growth since intake gas mass is reduced (as shown in Fig. 4(a)). As a result, exhaust gas mass per cycle is also reduced, and it limits the growth of exhaust gas exergy finally. As shown in Fig. 4(d), irreversible exergy loss per cycle also increases with gasoline engine speed increasing. Additionally, irreversible exergy loss per cycle is much larger than other kinds of exergy, and it plays a key role in exergy efficiency of gasoline engine as well as energy utilization efficiency.

Then, the distributions of exergy balance at gasoline engine full load are given, as shown in Figs. 5(a)−(e). Above all, the distribution of effective work is discussed. The percentage of effective work in total fuel exergy changes little when gasoline engine is at the low and medium speed, while it declines dramatically at high speed. At the speed of 6 000 r/min, the percentage of effective work is only 21.3%, which falls by nearly 8% compared to that at 2 000 r/min. This is because irreversible exergy loss increases rapidly at high speed and then affects the distribution of exergy balance. Actually, the percentage of effective work corresponds to the effective thermal efficiency, and both of them can evaluate the fuel economy of gasoline engine. The maximum percentage of heat transfer exergy is 13.3%, which appears at the speed of 1 000 r/min. While the minimum percentage is only 8% and it appears at the speed of 6 000 r/min. At low speed, since heat transfer time plays a leading role, heat transfer quantity per cycle comes up to the maximum value and then leads to the point that the percentage of heat transfer exergy also reaches its maximum. At high speed, the positive effect

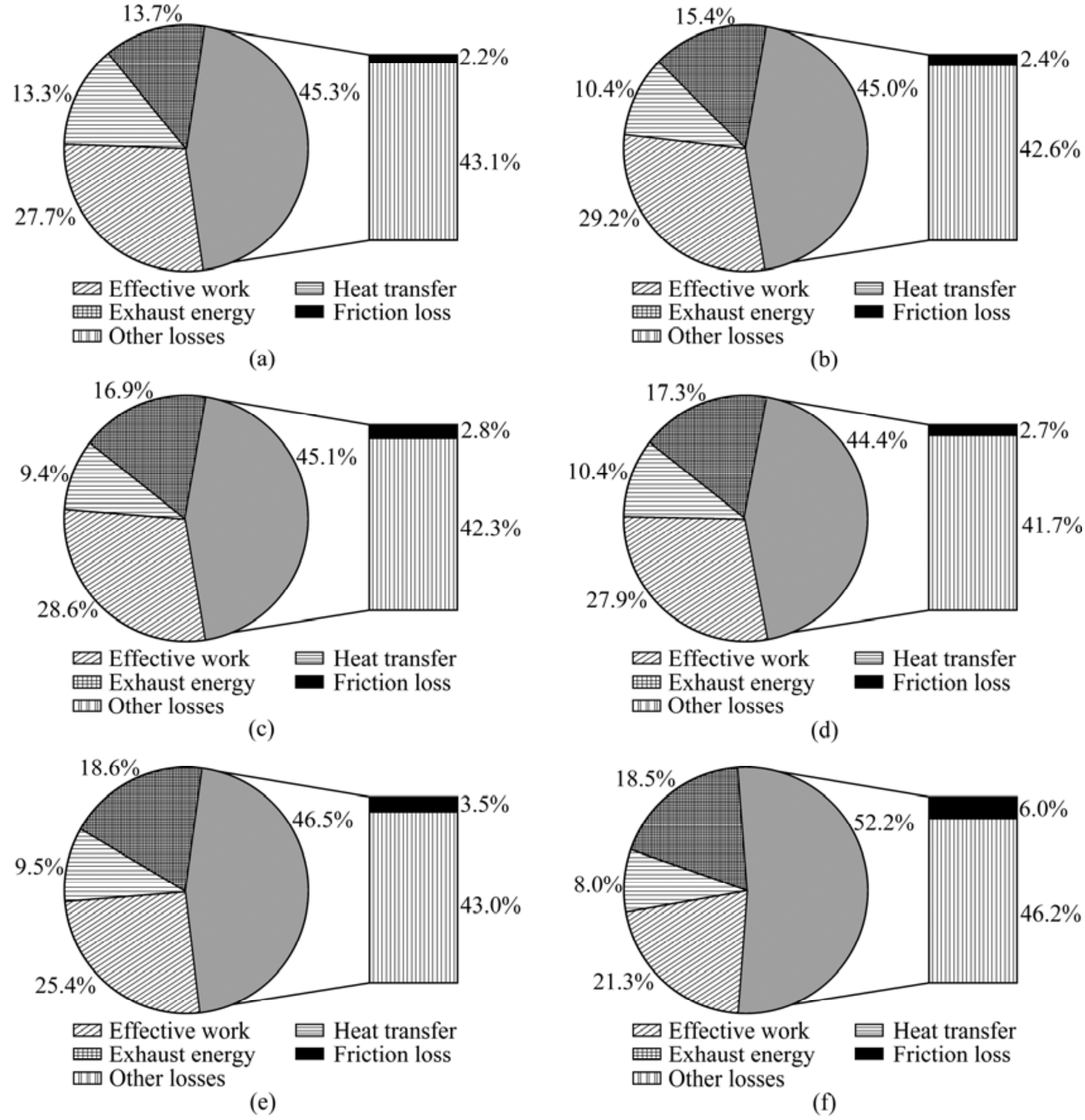


Fig. 5 Percentages of various kinds of exergy at full load: (a) 1 000 r/min; (b) 2 000 r/min; (c) 3 000 r/min; (d) 4 000 r/min; (e) 5 000 r/min; (f) 6 000 r/min

of in-cylinder temperature increasing cannot overcome the negative effect of heat transfer time decreasing. Finally, the percentage of heat transfer exergy declines. But at medium speed, the percentage of heat transfer exergy changes slightly because the influences of heat transfer time and in-cylinder temperature almost offset. The percentage of exhaust gas exergy always increases when speed ascends except at the highest speed of 6 000 r/min. In reality, exhaust gas exergy is determined by exhaust gas temperature and mass flow rate. Exhaust gas temperature increases with the speed, while exhaust gas mass flow rate changes at different speeds. As a result, the percentage of exhaust gas exergy has no growth at 6 000 r/min since exhaust gas mass flow rate declines. In Fig. 5, irreversible exergy loss is divided into friction loss and other losses, since friction work can be directly acquired via GT-power calculating. The percentage of irreversible exergy loss changes little at low and medium speeds, while it increases rapidly at 6 000 r/min. This phenomenon can be analyzed as follows. At the highest speed, combustion process turns worse because the combustion time is reduced and at the same time combustion temperature increases. Also, the turbulence of mixture gas in cylinder is enhanced. Moreover, the percentage of friction loss increases rapidly at the highest speed, as shown in Fig. 5(f). All those make the proportion of irreversible exergy loss increase dramatically.

4.2 Gasoline engine exergy balance at part load

Next, the relationship between exergy balance and gasoline engine load is discussed. Unlike diesel engine, gasoline engine load is adjusted by intake gas mass. Different loads require different intake gas masses, which results in different exergy balances. In this work, gasoline engine speed was fixed at 3 000 r/min while

load was changed from 0.2 MPa to 1.0 MPa. Figures 6(a)−(d) show effective work, heat transfer exergy, exhaust gas exergy and irreversible exergy loss per cycle at 3 000 r/min. As can be observed, effective work, heat transfer exergy, exhaust gas exergy and irreversible exergy loss approximately increase in linear with the increase of brake mean effective pressure (BMEP). This is because higher BMEP means more mixture gas (intake gas and fuel) and fuel exergy flow into cylinder. However, the increasing rates of various kinds of exergy are different from each other. The largest increasing rate appears in irreversible exergy loss, followed by effective work, then exhaust gas exergy, while the increasing rate of heat transfer exergy is the smallest. The differences of increasing rates and initial values determine the distribution and variation trend of various kinds of exergy, which are illustrated in the next section.

Figures 7(a)−(e) show the exergy balance of gasoline engine at different loads (speed of 3 000 r/min). As illustrated in Fig. 7, the higher the gasoline engine load is, the larger the percentage of effective work will be. For example, when BMEP increases from 0.2 MPa to 1.0 MPa, the percentage of effective work changes from 19.2% to 30.6%. This phenomenon is consistent with the variation trend of gasoline engine thermal efficiency. Whereas, the percentage of heat transfer exergy decreases gradually as BMEP increases. This is because the growth rate of heat transfer exergy is much lower than that of effective work and irreversible loss, as shown in Fig. 6. As the BMEP increases, the percentage of exhaust gas exergy grows all the time, but the growth rate is so little that it can be ignored. Although exhaust gas temperature increases with load increasing, the growth rate of exhaust gas temperature is very limited. With the increase of load, the percentage of irreversible exergy loss decreases. The reasons can be listed as follows. On one hand, gasoline engine experiences intake throttling at part load. The higher the BMEP is, the lower the throttling loss will be. On the other hand, as the load increases, the total fuel exergy grows rapidly while the friction loss almost has no change. As a result, the percentage of friction loss falls rapidly, as shown in Figs. 7(a)−(e). Based on the analysis above, the following conclusions can be reached. As gasoline engine load increases, the percentages of irreversible exergy loss and heat transfer exergy decrease while the percentage of exhaust gas exergy changes a little. However, the percentage of effective work always increases. That is to say, the exergy shifts from irreversible loss and heat transfer to effective work when

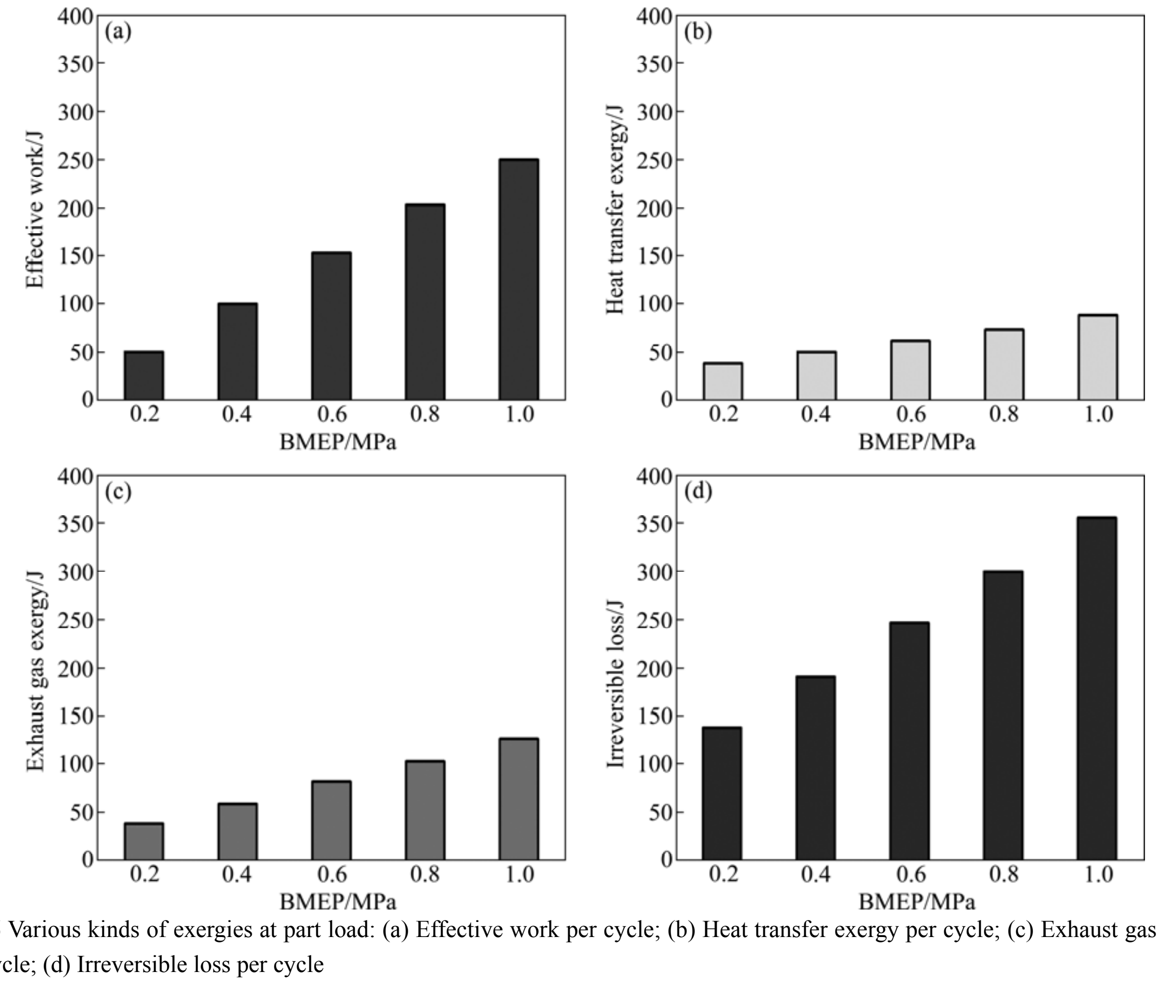
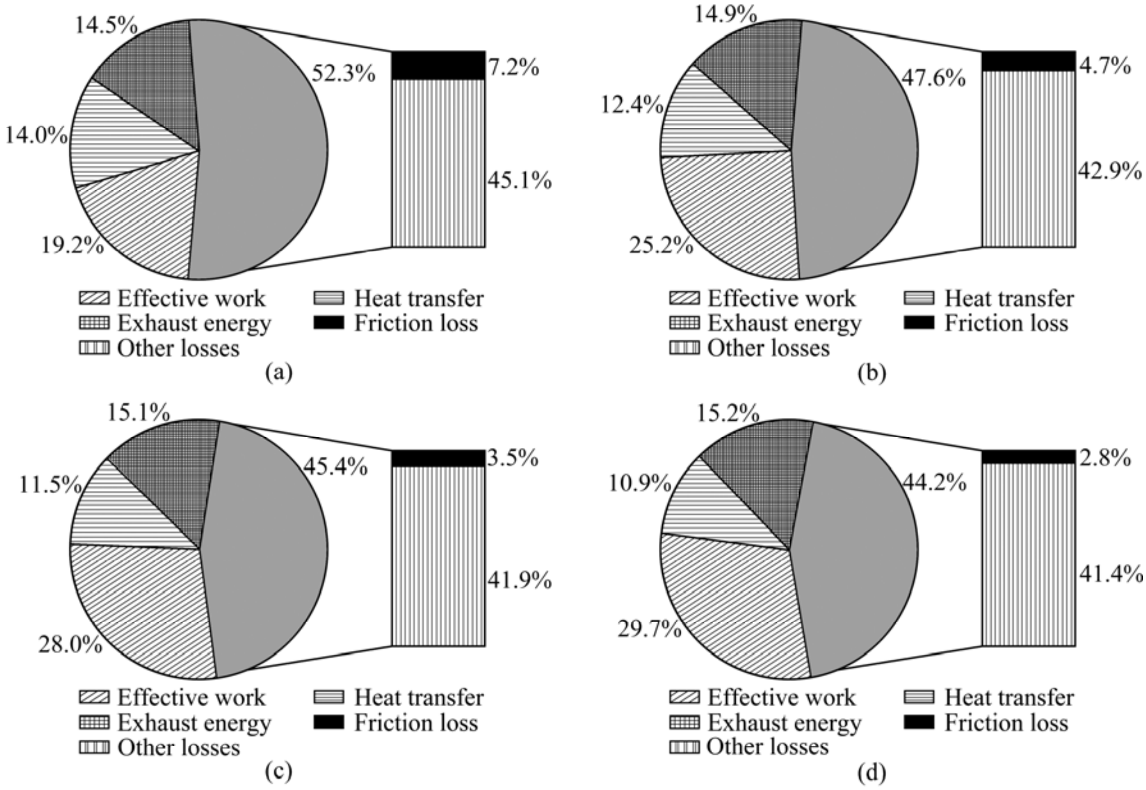


Fig. 6 Various kinds of exergies at part load: (a) Effective work per cycle; (b) Heat transfer exergy per cycle; (c) Exhaust gas exergy per cycle; (d) Irreversible loss per cycle



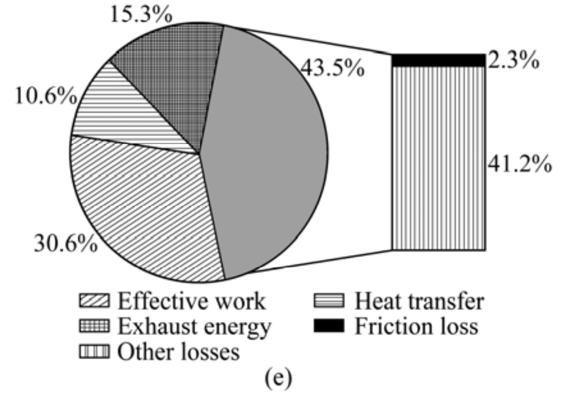


Fig. 7 Percentages of various kinds of exergy at part load: (a) 0.2 MPa; (b) 0.4 MPa; (c) 0.6 MPa; (d) 0.8 MPa; (e) 1.0 MPa

gasoline engine load increases. For this reason, to increase gasoline engine load is one of the best ways to improve its exergy efficiency. However, irreversible exergy loss takes the largest proportion under any circumstance. This phenomenon can be explained as follows. As irreversible loss is mainly dominated by combustion loss [6], the energy grade descends from chemical energy to thermodynamics energy during combustion process. In other words, irreversible loss takes the largest proportion because combustion is the strongest irreversible process. Therefore, how to reduce this part of exergy loss becomes a critical problem for improving gasoline engine exergy efficiency.

4.3 Approach for improving gasoline engine exergy efficiency

As it can be known through the above analysis, whether gasoline engine operates at full load or part load, the proportions of various forms of exergy from high to low is irreversible loss, effective work, exhaust gas exergy and heat transfer exergy. That is to say, irreversible loss always takes the highest proportion. Therefore, for the purpose of improving gasoline engine exergy efficiency, the first step is to reduce the proportion of irreversible exergy loss. In fact, irreversible loss is inevitable as the real cycle process is irreversible process, but it can be reduced through various means, e.g. selecting a higher working load and suitable speed according to Fig. 7 and Fig. 5, optimizing combustion process and intake process. In addition, exhaust gas exergy and heat transfer exergy are external exergy loss, and both of them can be reused by exhaust gas exergy recovery and cooling water exergy recovery [13−16]. Most of exhaust gas exergy can be recovered except that a small part of exergy is lost due to friction loss and exhaust throttling loss. However, most of heat transfer

exergy is lost during heat transfer process. The reason is that heat transfer temperature difference between in-cylinder gas medium and cooling water is very high.

5 Conclusions

1) At full load and part load (speed of 3 000 r/min), the proportions of various forms of exergy in gasoline engine from high to low are irreversible loss, effective work, exhaust gas exergy and heat transfer exergy. Irreversible exergy loss always takes the largest proportion, and it is the main factor constraining gasoline engine exergy efficiency.

2) The percentage of effective work fluctuates with volumetric efficiency at full load, while it always increases with BMEP at part load. Exhaust gas exergy is more sensitive to speed, and its proportion increases with speed except at the highest speed. At full load, the percentage of heat transfer exergy changes a little at medium speed, while it monotonically decreases with BMEP at part load. Irreversible loss is more sensitive to load. At part load, higher BMEP results in lower proportion of irreversible loss; at full load, the proportion of irreversible loss changes a little except at the highest speed.

3) To select a higher working load and suitable speed is one of the best ways to improve gasoline engine exergy efficiency. Meanwhile, to recover exhaust gas exergy and cooling water exergy is another good method to increase the total exergy efficiency of gasoline engine.

Acknowledgements

This research work is sponsored by the Scholarship Award for Excellent Doctoral Student granted by Ministry of Education, China.

References

[1] TANG Kai-yuan, OUYANG guang-yao. Higher internal combustion engine [M]. Beijing: National Defence Industry Press, 2008. (in Chinese)

[2] FU Jian-qin, LIU Jing-ping, FENG Ren-hua, YANG Yan-ping, WANG Lin-jun, WANG Yong. Energy and exergy analysis on gasoline engine based on mapping characteristics experiment [J]. Applied Energy, 2013, 102(2): 622−630.

[3] TAYMAZ I. An experimental study of energy balance in low heat rejection diesel engine [J]. Energy, 2006, 31(2): 364−371.

[4] YANG Xiu-qi. Exergy analysis on the working process of diesel engine [D]. Kunming: Kunming University of Science and Technology, 2004. (in Chinese)

[5] RAKOPOULOS C D, GIAKOUMIS E G. Simulation and exergy analysis of transient diesel-engine operation [J]. Energy, 1997, 22(9): 875−885.

[6] WANG Jian-ning. Energy balance analysis and exergy analysis on the thermodynamic cycle of a medium speed engine [D]. Wuhan: Wuhan University of Technology, 2010. (in Chinese)

[7] RAKOPOULOS C D, GIAKOUMIS E G. Second-law analyses applied to internal combustion engines operation [J]. Progress in Energy and Combustion, 2006, 32(1): 2−47.

[8] NIEMINEN J, DINCER I. Comparative exergy analyses of gasoline and hydrogen fuelled ICEs [J]. International Journal of Hydrogen Energy, 2010, 35(10): 5124−5132.

[9] AZOUMAH Y, BLIN J, DAHO T. Exergy efficiency applied for the performance optimization of a direct injection compression ignition (CI) engine using biofuels [J]. Renewable Energy, 2009, 34(6): 1494−1500.

[10] LIU Jing-ping, FU Jian-qin, REN Cheng-qin, ZHU Guo-hui, DENG Bang-lin, KESHAV V. Experimental comparision of heat and exergy balance in a turbocharged direct-injected gasoline engine [J]. Transaction of CSICE, 2013, 31(1): 65−71. (in Chinese)

[11] YAO Shou-guang. Thermodynamic system analysis on ship [M]. Beijing: Science Press, 2003. (in Chinese)

[12] LIU J P, BINGHAM J F. A study on the intake pressure wave actions and volumetric efficiency-speed characteristics of multi-cylinder engines [J]. Transactions of CSICE, 1997, 15(2): 138−150.

[13] HE Mao-gang, ZHANG Xin-xin, ZENG Ke, GAO Ke. A combined thermodynamic cycle used for waste heat recovery of internal combustion engine [J]. Energy, 2011, 36(12): 6821−6829.

[14] FU Jian-qin, LIU Jing-ping, YANG Yan-ping, REN Cheng-qin, ZHU Guo-hui. A new exhaust energy recovery method for improving IC engine performance: Steam turbocharging [J]. Applied Thermal Engineering, 2013, 52(1): 150−159.

[15] LIU J P, FU J Q, REN C Q, WANG L J, XU Z Z, DENG B L. Comparison and analysis of engine exhaust gas energy recovery potential through various bottom cycles [J]. Applied Thermal Engineering, 2013, 50(1): 1219−1234.

[16] FU Jian-qin, LIU Jing-ping, REN Cheng-qin, WANG Lin-jun, DENG Bang-lin, XU Zheng-xin. An open steam power cycle used for IC engine exhaust gas energy recovery [J]. Energy, 2012, 44(1): 544−554.

(Edited by YANG Bing)